U. S. Department of Agriculture Forest Service

STUDIER ÖVER KLIMATETS HUMIDITET I SVERIGE

STUDIES ON THE HUMIDITY OF SWEDEN'S CLIMATE

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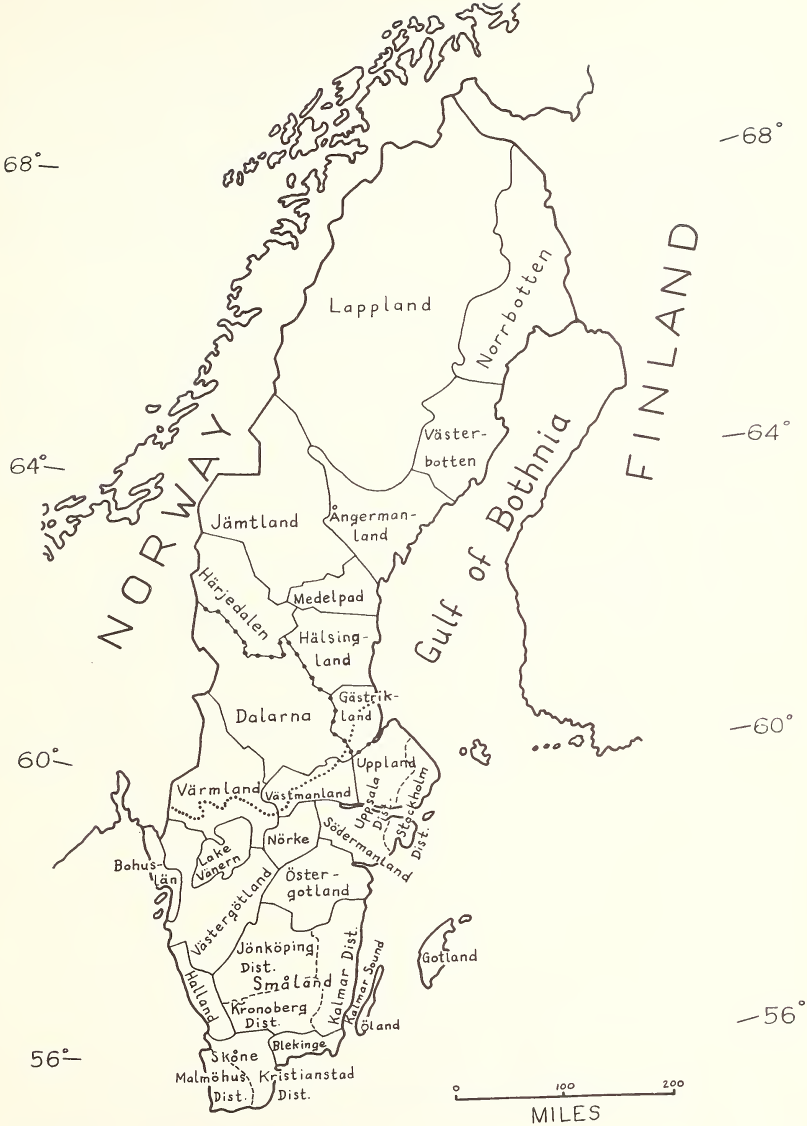

Southern limit of Norrland
as politically defined
as biotically defined in SJÖRS

TRANSLATOR'S PREFACE

Olof F. S. Tamm is perhaps best known in the United States as an authority on forest soils, and especially for his "Northern Coniferous Forest Soils."1/

In evaluating his system of climatic description consider that it was developed and applied in a country extending over more than 13 degrees of latitude, whose southern end is in the deciduous forest biome and whose northern end is north of the coniferous forest limit in a tundra - birch scrub ecotone.

A problem in reading this paper is the frequent reference to locations, especially provinces, unfamiliar to most Americans. Therefore a map is presented that shows Swedish provinces. In the text places shown on the map are marked (*). Tamm used both old province names and the names of modern administrative districts. The map shows the names used in the text. Thus the old provinces of Småland, Skåne, and Uppland are shown as well as the modern districts, Kalmar, Kronoberg, Jönköping, etc., which comprise them. However, most modern districts coincide essentially with single old provinces; for these Tamm used the province names, and these are also used in translation and on the map.

The term "Norrland", appearing often, means "north land". As a climatic-floristic area, it is that part of Sweden in the taiga or boreal forest zone which includes about 2/3 of Sweden. Its delineation on the map is from Sjörs "Nordisk växtgeografi."2/ In a more restricted sense it is the country north of Dalarna.

With the exception of plate 1 and table 5, all figures, tables, and plates in the translation are in the back. Plate 1 has not been reproduced. Table 5 is included in the text.

1/ Tamm, Olof F.S. 1950. "Northern Coniferous Forest Soils" Scrivener Press. Oxford. 253 pp.

2/ Sjörs, Hugo. 1956. "Nordisk växtgeografi." Svenska Bokförlaget. Bonniers. Stockholm. 229 pp.

Foreward

In 1952 the author began to study the humidity of the Swedish climate on the basis of evaporation and runoff in the drainages of a number of streams. The first results were presented in a lecture before the Royal Academy of Agriculture (Tamm, 1954). At the same time Dr. L. Turc at the Laboratoire des Sols at Versailles worked on a partially similar problem but from a universal point of view. He presented his studies in a doctoral dissertation: "Le Bilan d'eau des sols: Relations entre les precipitations, l'evaporation, et l'ecoulement," and defended it in April, 1953 (Turc 1954-55). In 1956 the author heard of Turc's important work. Its results shall be touched upon in the following. During a visit in Versailles, I had the good fortune to discuss certain problems with Dr. Turc.

My studies are based on observations from the Meteorological and Hydrological Institute of Sweden (SMHI). Also, to a large extent maps have been used which are based on observations of the institute. These maps were prepared at the Cartographic Institute under the direction of Dr. Magnus Lundqvist. The institute also assisted in preparing the maps used in this treatise. In the final editing of the maps I also had considerable help from Dr. Lundqvist's successor, map-editor, O. Hedbom. Technologist Erik Jonsson assisted in the regression analyses, as did Prof. T. Troedsson, and B. Matern, mathematician, of the National Forest Research Institute. This paper includes a report by Mr. Matern of his computations. A comprehensive job of tabulation and drafting has been carried out at the Institute of Forest Soils of the Forestry College, by Miss Margareta Wiberg and assistants, Thorsten Nilsson, Yngve Jonsson, Ulf Buskqvist, and Sven-Birger Petersson-Arm, as well as forestry student Gösta Nulden. Dr. H. Eidmann has kindly reviewed and corrected the German text.

To the institutions and persons who in different ways helped me in my undertaking, I address my warm thanks. I want first to mention the Meteorological and Hydrological Institute of Sweden and especially the late Bureau-Chief, R. Melin; the late director, A. Ångström; and Bureau-Chief, C. C. Wallen; as well as to the Cartographic Institute, Ltd., and its Dr. M. Lundqvist.

The Fund for Forestry Research has born the unavoidable and rather large costs which were associated with the making and reproducing of the maps, as well as certain other publication costs. To the Fund's board of directors, I address my warm and respectful thanks.

The Forestry College, May, 1959.

Olof F. S. Tamm

INTRODUCTION

Ever since the famous German geographer Penck divided the climate of the Earth into arid, humid, and nival with regard to the conditions of precipitation, evaporation, and runoff, workers in soil science, ecology, plant geography, and other closely related branches of natural science have felt a great need of a quantitative expression of climate as it influences water available to plants, in other words, an expression of the <u>degree of humidity of the climate</u>, or simply its <u>humidity</u>. This depends not merely on precipitation but also on evaporation. Evaporation is in turn a function of the energy supply, of which the air temperature is a measure.

Of course meteorologists and hydrologists have also interested themselves in these problems, especially in connection with calculation of water power resources. In Sweden, as in other countries, stations have been established for the measurement of streamflow in a large number of streams. Simultaneously precipitation has been determined at a number of points within their watersheds above the gaging stations. Since all these measurements were followed up over considerable periods, good expressions have been produced not only for average annual precipitation (in this paper always designated as P), but also for average annual runoff (R), and for the average annual evaporation from soil and vegetation, the so-called evapotranspiration (E), which is the difference P-R.

Over long periods it is not necessary to take into consideration temporary ground water storage in the soil. Also, in Sweden it can usually be assumed that noticeable ground-water flow by the gaging stations does not take place.

In this paper the average annual temperature of the air at standard instrument level, where measurement of the general air temperature is the object, is designated T.

At SMHI there have been drawn on a map of Sweden isolines for evapotranspiration, E, based on investigations of the sort stated above (Bergsten, 1954, page 7). See figure 3. The average annual runoff itself is an excellent measure of the degree of humidity in a climate that is humid in the sense used by Penck. In such a climate there is a precipitation surplus that causes water courses of different sizes. Thanks to the work of the SMHI, R is known for a large number of drainages in different parts of our country.

In spite of meteorologists and hydrologists having thus produced good quantitative expressions for climatic humidity as well as for evapotranspiration, researchers in other fields have not been satisfied with this solution of the problem. The reason is that the values obtained refer to the entire drainage, which is usually extensive, including considerable dissimilarities in both air temperature and precipitation. One does not arrive at the local variations in humidity, which can be very considerable.

Therefore other expressions have been sought for the humidity or aridity of the climate, expressions that can be derived from the meteorological observations carried out at many points scattered over a large area. This approach is accompanied by relatively detailed maps.

Lang (1920) proposed the use of the quotient of P:T. His expression is the simplest conceivable function that increases with rising P and falling T. De Martonne (1926) changed this quotient to P:(T+10) so that in cold climates the denominator does not approach zero. Symkiewicz (1923) divided P not by a temperature expression but by an expression of the effect of evaporation, which could be calculated from data on atmospheric humidity. A. Meyer proposed the relation between P and the saturation deficit of the air. Axel Wallen (1927) recommended the relationship P:E, with E determined with the help of runoff in the drainages.

Hesselman (1932) examined all these methods. He found that for Sweden De Martonne's was most suitable. He emphasized that a quantitative measure of the degree of humidity of a climate should permit calculation for a large number of separate points, to permit relatively detailed cartographic presentation. He calculated De Martonne's values for 187 Swedish meteorological stations scattered all over the country. On this basis he developed a map on which Sweden is divided into six zones with different humidity numbers:

Zone 1, Subarid Regions,	Humidity Number <30
Zone 2, Continental Regions,	Humidity Number 30-34
Zone 3, Transition Regions,	Humidity Number 35-39
Zone 4, Subhumid Regions,	Humidity Number 40-49
Zone 5, Humid Regions,	Humidity Number 50-59
Zone 6, Superhumid Regions,	Humidity Number >60

Hesselman's results were accepted in Sweden, and De Martonne's number subsequently played an important role here. However, it is not very sensitive to temperature and lacks clear physical meaning. Concerning Hesselman's terminology it can be objected that the word humid is used for a particular zone and the term continental in a special sense, deviating from current usage. Therefore, in this paper Hesselman's designations are not used except for subarid and superhumid.

Ångström (1936) said a good system of humidity evaluation should have a clear physical meaning. De Martonne had already calculated humidity values for separate months, which Ångström pointed out fulfilled his (Ångström's) requirement.

Finally it may be mentioned that the plant geographer Emberger (1942) presented a climatic function that included both the humidity and the continentality of the climate (see Tamm, 1954). It has been used successfully in connection with both plant geographic and pedalogic investigations. (For the latter see Duchaufour, 1948.)

The best expression for climatic humidity in a humid country like Sweden should be the difference P-E, that is, the difference between the average annual precipitation and average annual evapotranspiration, assuming that this difference can be calculated for definite points from simple meteorological observations. P-E is a number with concrete meaning--the fractional part of the precipitation that is not evaporated but forms ground-water and surface-water and gives rise to springs, creeks, and rivers. It is clear that the heart of the problem is to find a method for calculation of E from general meteorological observations. E results from the energy supply of which T is an expression. There should be a functional relation between E and T. This relationship should be found. The difference P-E can then be figured. In this paper, this difference is called H, that is, the <u>humidity number</u> or <u>humidity value</u>.

Derivation of Functions for Computation of E from T

Assume one has a usable expression for average annual temperature, T, within an entire drainage (above a gaging station). One would also know the average annual runoff (R). If, thanks to a considerable network of precipitation stations, the average annual precipitation (P) was known the difference (P-R), which is E, could be found. Then one should be able to derive the function that expresses the general relation between E and T.

To try to solve this problem, the author asked for and got the necessary meteorological and hydrological data (except the T values) from the then Bureau Chief at SMHI, R. Melin. The data were from a number of suitable drainages scattered over Sweden (see Tamm, 1954, table 1). They were 25 in number, and all lay outside the mountain region whose strongly variable precipitation in most cases is not known by direct precipitation observations. (See figure 4 for mountain region.) The data obtained for the different drainages were:

1. The average annual precipitation from 1921-1950,
2. The average annual runoff for the same period, and
3. The lake percent, which was not permitted to deviate too much from normal.

All the drainages were essentially forested moraine areas. They could be designated as Swedish normal-terrain, however, with considerable topographic differences of course. In regard to the sources of error in measuring runoff, refer to R. Melin (1955, beginning with page 14). Regarding error sources in measuring precipitation, see C. C. Wallen (1951) and F. Bergsten (1954).

Average annual temperatures in the drainages were determined in this way: On a map of annual isotherms in Sweden for the period 1901-1930, from "Atlas of Sweden", with a scale of 1:4,000,000, the boundaries of the different drainages were drawn. The gaging stations

were located, with the general maps used as guides. After this the drainages were delineated to include only what lay above the gaging stations. This was possible with the help of the special maps of the drainages of our streams published by SMHI. In this certain permissable approximations were made. On the working map the 25 drainages were divided by the annual isotherms into a number of segments. A segment between two isotherms was considered to have an average annual temperature midway between them. By considering the areas of the different segments, determined by planimetering, a value could be calculated for the average annual temperature in each drainage above the gaging station. The T-values obtained were for the period 1901-1930. This is an unavoidable but rather insignificant inconvenience. They are based on Ångström's work (1938), where the sources of error in temperature measurements are discussed.

From the P-values obtained from SMHI for the different drainages the runoff values for the same drainages were subtracted. Thus their E-values were established. In a graph (figure 1) the E-values were then marked off along the Y-axis and the T-values along the X-axis. The result was a swarm of points, which by regression analysis were smoothed to a straight line whose equation was:

$$(1) \quad E = 220.9 + 30.4\ T$$

The correlation coefficient was 0.937 ± 0.024. For the data used in the computations refer to Tamm, (1954). The gap in the point-swarm between the T-values 2 and 3.9 is due exclusively to the circumstance that no data for drainages in this interval were supplied by SMHI. Turc's previously mentioned work (1954-55, page 140) includes two Finnish watersheds in this interval; their E-values fell on or very near the straight line in figure 1, as did two E-values for Swedish drainages, which the author figured from data from SMHI. With this, equation 1 was regarded as entirely satisfactory.

Since P and T are known for a large number of points in Sweden, extensive calculations of E- and H-values could now be carried out. Equation 1 as well as a table with a limited number of T-, P-, E-, and H-values corresponding to each other was presented in the previously mentioned paper (Tamm, 1954). However, the P-values in the table, unlike those delivered earlier for the 25 drainages by SMHI, had to be gotten from C. C. Wallen's investigation (1951), which included a different period, namely 1901-1930. Soon, however, figures were published for the average annual precipitation during the "right" period, 1921-1950 (Bergsten, 1954). Subsequently all H-values were calculated or estimated on the basis of Bergsten's figures and laid out on a map. On the basis of this point-map, Dr. Magnus Lundqvist then worked up a map with isolines for the H-values, of which more shall be said in the following. The rough draft of this map was complete when the author learned of a body of data from an additional number of drainages that was published and could be used.

DERIVATION OF A NEW FUNCTION - In 1955 there appeared R. Melin's important book, "The Waterflow in Sweden's Rivers." In this large tabular work are figures for the average flow in the rivers in liters per second per square kilometer of drainage area for the period 1921-1950. These could be converted to mm per year and thus to R-values. On the other hand there was no information on the average annual precipitation for the drainages.

From Melin's book the necessary figures, aside from T and P, were taken for all the watercourses, which fulfilled the requirements earlier established; the sum of acceptable drainages rose to 54. A small river, Röjdån, in western Värmland* near the Norwegian border, had a very peculiar value. In a consultation with Bureau-Chief C. C. Wallen at SMHI he explained that the precipitation in Röjdån's strongly dissected drainage was not satisfactorily known. Its data were excluded. There remained data for 53 usable drainages.

The average annual precipitation for the new drainages had to be determined from maps. Thanks to the cooperation of Dr. Lundqvist, I now had at my disposal an isotherm map with 0.5 centigrade degree intervals, in a scale of 1:1,500,000 (about 24 miles to the inch). On this isotherm map Dr. Lundqvist drew isohyets from Bergsten's (1954) map of average annual precipitation in Sweden, with 50 mm intervals. In this he made use of an existing rough draft map with a larger scale than that published. Then the drainages above the gaging stations were drawn on a transparent map of the same scale as the working map with its annual isotherms and annual isohyets. T as well as P could now be calculated for the different drainages according to the method given above, that is by planimetering the segments defined by isolines and the calculation of average values based on the weighting of areas with different T- or P-values. T was also redetermined for the 25 old drainages, since the new working map had isotherms with half-degree intervals and consequent increased certainty. The differences between the old and new temperature determinations for individual drainages were: in 11 cases 0; in 7 cases 0.1 centigrade degree; in 5 cases 0.2 degree; and in 1 case each 0.3 degree and 0.4 degree.

From Melin's book the following additional data were recorded:

1. The name of the stream and the gaging station,
2. The area of the drainage above the gaging station,
3. The lake-percent of the drainage area,
4. Its average altitude,
5. The difference between the average and highest altitudes, which to some extent expresses the degree of brokenness of the topography and is designated B, and
6. R (runoff) and E.

All this is assembled in table 1, along with the T-values calculated for the drainages by the author, and their P-values, 25 of which were provided by SMHI as mentioned and then calculated as described above.

On the basis of the values of E and T given for the 53 watersheds in table 1, a new diagram was constructed (figure 2), and a new function figured in the same way as equation (1). It is:

$$(2) \quad E = 225 + 28.1\ T$$

The correlation coefficient is 0.909 ± 0.024. This is somewhat less than the previous correlation coefficient but has the same average error. Equation (2) was used to compute E- and H-values in a paper on the superhumid region of southwestern Sweden (Tamm, 1959). It should not be the final expression, however.

Because of the great increase in the number of usable drainages, it should be possible to demonstrate the influence on evapotranspiration of factors other than T. The author had felt it would be possible to trace graphically certain tendencies with lake-percent and possibly also with respect to P and B, the latter of which is strongly correlated with general altitude. Therefore table 1 and the diagram in figure 2 were delivered to B. Matern, mathematician at the National Forest Research Institute. Mr. Matern kindly undertook to evaluate the material statistically, and to seek to establish a fundamental influence on E of some factor other than the temperature. Matern's account of his work, including derivation of several new functions, follows below. Of these functions, equation (3) is considered the best for calculating E.

CERTAIN STATISTICAL COMPUTATIONS

By B. MATERN

DESIGNATIONS AND MATERIAL:

Evapotranspiration in mm per year	(E)
Average annual air temperature, ° C	(T)
Lake-percent	(S)
Average annual precipitation, mm	(P)
Brokenness index (difference in meters between maximum and average altitude)	(B)

The values of E, T, S, P, and B for all 53 drainages are in table 1.

COMPUTATIONS:

The observed values of E have been smoothed with several different regression functions. When E is presented as a linear function of T alone the relation is:

$$(3)\quad E = 221.5 + 29.0\ T$$

The dispersion (standard deviation) of the 53 observed E-values around the regression line E-values calculated with Equation 3 is 27.8 mm, while the standard deviation around the average E-value is 69.6 mm.

If S (lake-percent) and ST are also included in the smoothing function, one obtains:

$$(4)\quad E = 227.4 + 21.8\ T + S\ (-0.869 + 0.900\ T)$$

The standard deviation of observed E-values around equation 4 is 25.3 mm.

If only T and ST are included in the smoothing function, the results are:

$$(5)\quad E = 222.3 + T\ (22.7 + 0.737\ S)$$

with a standard deviation of 25.1 mm around the regression.

The average error of the constants in the smoothing functions is shown in table 2. The table also shows the result of a smoothing in which, besides the variables in equation 4, P and B were also used. The standard deviation around this function, designated in the table as equation number 6, is 24.3 mm.

In elaboration, table 3 presents the result of the smoothing in an analysis of variance. There a seventh smoothing function is also shown, in which enter the variables T, H, and B. It was computed only to permit calculation of the F ratio given in the lower part of the table.

COMMENTS:

A. The analysis indicates a significant correlation of E and S. On the other hand, no clear decision is possible on a correlation with P or with B. The partial correlation between E and P (T, B, S, and ST eliminated) is no less than +0.24; the deviation of this coefficient from zero is not significant, however.

It should be pointed out that the current criteria of significance in regression analysis, which have been used here, are

based on certain assumptions often not satisfied in a series of observations from different geographic areas. These assumptions also lie behind the estimates of average error in table 2. Therefore one must keep in mind that significance may be more formal than real.

B. Equations 4 and 5 differ somewhat in the way in which the influence of lake-percent is expressed. The following simplified model can be said to lie behind both. For evaporation from a water surface,

$$E_1 = a_1 + b_1 T \text{ applies;}$$

while for evapotranspiration on land,

$$E_2 = a_2 + b_2 T \text{ applies.}$$

Thus for a drainage with lake-percent S, this relation should prevail:

$$E = \frac{S}{100} E_1 + \left(1 - \frac{S}{100}\right) E_2$$

By setting S = 0 and S = 100 in equation 4, one gets these estimates of E_1 and E_2:

$$E_1 = 140.5 + 111.8\ T \qquad E_2 = 227.4 + 21.8\ T$$

The difference between the constants, 140.5 and 227.4 is relatively small in relation to its average error, shown in table 2. Therefore, it may be of some interest to try smoothing with the assumption $a_1 = a_2$. This hypothesis implies that the evapotranspiration is independent of the lake-percent when T is about zero. It is this kind of smoothing that gives equation 5. With it is obtained:

$$E_1 = 222.3 + 96.4\ T \qquad E_2 = 222.3 + 22.7\ T$$

It should be mentioned that the coefficient for T in the formula for E_1 has a rather high average error (96.4 ± 19.0).

C. The standard deviation around the smoothing equations, as shown by the previous section, is about 25 mm. This amount can be conceived of as a measure of the range of observation error, and in the equation is not assigned to any of the factors that could be thought to affect evapotranspiration.

If by one of the means common in statistics one divides the variance of the E-values into 2 components, in the most complete of the equations one finds the factors considered to account for 88 percent of the variation, while other factors and observation error account for 12 percent. In equation 3 only T is considered; it accounts for 84 percent of the variation in E-values.

FURTHER DISCUSSION OF EVAPOTRANSPIRATION

THE MOST IMPORTANT RESULTS OF MATERN'S ANALYSIS

From this it is clear that, in addition to average annual temperature, the lake-percent has a noticeable influence on E.

The remaining factors analyzed, namely P and B, the latter strongly correlated with average altitude, do not demonstrate any certain influence. Even the lake-percent is inconsiderable; its influence is little, compared to that of the average annual temperature of the air. Therefore, one can profitably use equation 3, which like equation 1 and 2, is valid for Swedish normal-terrain outside the mountain region and including lake areas. Normally a drainage has a lake-percent of 7-8. In thatconnection it must be pointed out that at present it is impossible to get a peat-land percent within the different drainages. This very probably varies with lake-percent, and may affect a certain slight increase in E.

Equation 3 differs insignificantly from equations 1 and 2. In the data from drainages on which equations 2 and 3 are based there is no gap between T-values $+2^{o}$ and $+3.9^{o}$ such as was pointed out in connection with Equation 1. All three equations give very similar E-values. In figure 2, however, the dispersal around the straight line that represents equation 3 is somewhat larger than that around the straight line representing equation 1 (figure 1). It looks as if the first 25 drainages worked with were somewhat "better" than those later made available. The differences between the E-values computed by means of equation 3 and equation 1 for different values of T are shown in table 4. They must be regarded as very insignificant. This is especially apparent when one figures them as percentages. Therefore, there is no reason to repeat the comprehensive calculations and drafting already carried out with the aid of equation 1 before equation 3 was derived. Moreover, one actually cannot with complete certainty assert that equation 3 is really better than equation 1. The maps presented herein are based on computations with equation 1, which was published in 1954. For subsequent computations, however, equation 3 is considered best until an equation can be produced based on better data.

RELATIONS BETWEEN E AND DE MARTONNE'S INDEX

Ångström (1958, page 75) has made some interesting deductions based on equation 1. He has pointed out an approximate relation between the E-value and De Martonne's number, which therewith gets a desired physical meaning. His deductions can be carried through with better advantage on the basis of equation 3. This can be written:

$$E = 29.0 \ (T + 7.64)$$

Ångström's basis is the close resemblance of the expression $(T + 7.64)$[1] to the denominator $(T + 10)$ in De Martonne's function. If De Martonne's number is designated H_M, we can derive the following relation, which demonstrates Ångström's line of thought:

$$\frac{H_M}{29.0} = \frac{P}{a \cdot E}$$

where "a" is $\frac{T + 10}{T + 7.64}$

In Sweden this latter expression varies insignificantly with T. Therefore, considering the approximations and smoothings in the formulae used it can be regarded as rather constant for Swedish conditions. De Martonne's number, H_M, is then directly proportional to the relationship between average annual precipitation and average annual evapotranspiration. The proportionality factor is 24. (With the values available to Ångström, it is 25.)

With these deductions of Ångström's, De Martonne's annual number gains a meaning reminiscent of A. Wallen's above-cited expression P:E, the latter being transformed into De Martonne's number by multiplying by 24.

In this connection it may be pointed out that Turc (1954-55, page 115) has also reached a similar result. He established that in its original form De Martonne's number is approximately proportional to the relationship P:L within climatic regions whose T-values lie between 0 and 15. ("L" is Turc's symbol for potential evaporation. Translator.) According to Turc, in a climate like that of Sweden L is interchangeable with E. Thus Turc's work points up this relation of De Martonne's number to the ratio P:E in Sweden.

As an addition to these viewpoints of Ångström's and Turc's, it may be pointed out that De Martonne's equation can advantageously be changed to the following:

$$(8) \qquad H_q = \frac{P}{T + 7.64}$$

In this equation H_q is a new expression of the degree of humidity, much resembling De Martonne's. It also equals $\frac{29.0\ P}{E}$. This expression is valid in Sweden without the approximations that are part of the factor "a" discussed above. H_q assumes the value 29.0 when E = P--that is, at the limit between humid and arid climates.

Although the number H_q indisputably has certain merits, this is no reason to abandon the expression P - E as a measure of general climatic humidity in Sweden. On the other hand H_q may deserve discussion later when the question arises of characterizing the humidity conditions of individual months or seasons.

1/ That is to say, the corresponding part of equation 1, $(T + 7.4)$.

SCHOFIELD'S VIEWS ON EVAPOTRANSPIRATION

Schofield (1956, page 2) has asserted that air temperature is a poorer expression of the energy supply to ground and vegetation when terrains at different altitudes are compared. He states the energy supply varies considerably with several other factors not expressed in T. Turc (1954-55, pages 48 and 49) has discussed these problems thoroughly. He points out the following five factors, apart from falling temperature, which affect E with increasing altitude:

1. Increased evaporation due to decreasing atmospheric pressure.
2. Increased evaporation due to more intense irradiation.
3. Because snow-cover is more prevalent at higher altitudes, more of the incident solar energy is reflected, lessening evaporation.
4. Because precipitation occurs at lower temperatures at high elevations, evaporation is less there.
5. Because broken topography is more common at high altitudes, quick runoff is promoted there. This lessens evaporation.

Certain of these factors counter others. The dropping of air temperature with increasing altitude certainly expresses a generally decreasing supply of energy to the air layers near the ground, but due to the mentioned relations of radiation and evaporation small anomalies arise. According to Turc, however, in order to point out an altitudinal influence other than that expressed by decreasing T-values, one must work with great height differences, as in the Alps. In Sweden, outside the mountains, altitudinal differences are obviously entirely too small. Matern could not demonstrate any influence of B on E, and B is a measure of altitude. Of the 53 drainages on which equation 3 is based, 44 have an average altitude of between 100 and 400 m. For 3 it lies a little above 400 m, and for 6 under 100 m. One can not expect a noticeable influence of altitude in this material except that expressed in T.

TURC'S INVESTIGATIONS (1954-55) OF THE WATER BALANCE IN THE SOIL AND RELATIONS BETWEEN PRECIPITATION, EVAPOTRANSPIRATION, AND RUNOFF

These investigations are partly observations of precipitation and runoff and partly lysimeter investigations. The former are of the greatest interest here. Turc presents data from 254 drainages divided among regions scattered all over the world. To begin with, he establishes that, considered broadly, E must, above all, depend on T and P. Consequently, the function E = f (P, T) should be looked at more closely. By means of a thorough mathematical analysis, with runoff

from the investigated drainages as a control, Turc arrives at the following system of equations:

$$(9) \quad E = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}}$$

$$(10) \quad L = 300 + 25\ T + 0.05\ T^3$$

A prerequisite for the validity of equation 9 is that $\frac{P^2}{L^2}$ is less than 0.1. Otherwise E = P, which means the climate is too moist to be classified arid. The symbol L is explained as follows: If in an arid climate there is a change in the direction of decreasing aridity, E increases in proportion to P. If little by little the climate becomes humid, E reaches a maximum value and increases no further provided T is constant. This maximum value has been designated L and can be regarded a function exclusively of T, in a given climatic type. R. Melin has orally stated to the author a similar line of thought; it seems to be general among our hydrologists.

Further, Turc has arrived at the following relation, in which he replaces L with lambda to mark it as being valid only within an area where T is less than 14° C. and P is greater than 500 mm (Turc, p. 16).

$$(11) \quad \lambda = 280 + 25\ T$$

The climatic type considered here by Turc includes Sweden's climate apart from some insignificant strips where P lies below 500 mm. Also there is a striking similarity between Turc's equation and equations 1, 2, and 3. As a rule, λ in equation 11 can be replaced by E in Sweden. As far as our country is concerned Turc's general analysis of E's dependence on P and T leads to a relation of the same type as the equations (1, 2, and 3) based on measurements in Swedish drainages. This is no reason for us to abandon these equations for equation 11, since they are much better related to the runoff and evaporation in Swedish watersheds. The 53-watershed basis of equation 3 is a considerably more homogeneous, thus in a sense a better, body of data than that used by Turc.

Turc's investigations of E, R, P, and T confirm the calculations presented above. His comprehensive work includes critical discussions of a large number of conceivable influences on E, most of them graphically illustrated. This gives a good basis for continued studies in different parts of the world. Moreover, in the latter part of his treatise he has tied in the results of lysimeter investigations in a very creditable way.

A MAP OF EVAPOTRANSPIRATION IN SWEDEN

Equations 1, 2, or 3 permit the mapping of E in Sweden outside the mountain region. For reasons given above, equation 1 was used for the map presented here. To arrive at isolines of E, successive E-values with 50 mm intervals were plugged into equation 1 and the corresponding T-values calculated (see table 5).

Table 5: E-values with corresponding T-values.

E	T
450 mm	7.54° C
400	5.89
350	4.25
300	2.60
250	0.95
200	-0.69

On a map of Sweden Dr. Lundqvist now drew isotherms (broad solid lines) for the T-values in table 5. (See figure 3.) For comparison, on the same map Bergsten's (1954, page 7) isolines of evapotranspiration have also been drawn with light double lines. These latter are based on runoff and evapotranspiration within entire drainages, and in the mountain region largely on the thorough investigations of the water economy carried out by R. Melin (1942) in the Malmagen mountain district.

The deviations between Bergsten's isolines of E and the new lines of isotherm character are of great interest. Agreement must be regarded as good for the lines of 200, 250, 300, and 350 mm. As they should, the new isolines give a more detailed picture of evapotranspiration than do Bergsten's. In Norrland* they bend somewhat up the large valleys where the E-values undoubtedly are higher than on the divides. On the other hand, in the mountain region Bergsten's method is the only one usable. Even in a zone adjacent to the mountain chain the results of the isotherm method are uncertain for several reasons. This has been indicated by drawing the isolines as broken lines.

South of the limit of the Norrland terrain the isotherm method gives a far more detailed and finely shaded picture of evapotranspiration than the old method did. The reason is clear. Within the narrow coastal plains not many drainages have been investigated. The rivers in Småland*, Blekinge*, and Halland* have the greatest part of their basins in the interior of southern Sweden, and they represent only in small part the coastal strip. According to Bergsten's map, Skåne has an E-value of less than

400 mm, which seems peculiar considering that several drainages in the surrounding country lie above that value according to the measurements of the hydrologists. Clearly the isotherm method gives a truer picture of E in southern Sweden than is permitted by the older method. In this connection it may be pointed out that at the SMHI they have long used a rough estimate for E south of the Norrland terrain, 360 mm (Tryselius, 1946), which according to Bergsten (1950) should be raised 10 percent.

SOME GENERAL CONCLUSIONS ON EVAPOTRANSPIRATION

The E-values derived from T obviously are valid for Swedish normal terrain outside the mountain region. Apart from the largest well-cultivated plains areas about 63 percent of the area outside the mountains is forested, about 21 percent is bog, about 8 percent is lakes and rivers, about 4 percent is cultivated, and another 4 percent is bedrock or extremely stony ground. The lakes raise E-values somewhat, and rock outcrops and possibly cultivated soils lower them. In all probability bogs increase E-values, but clearly less than do free water surfaces. Thus the formula-derived E-values of figure 3 are representative but approximate expressions of evapotranspiration in the forested morainal terrain of our country.

With the development of equations (1) and (3) the problem of calculating evapotranspiration, E, from average annual temperature, has a simple and satisfactory, though approximate solution as far as Sweden is concerned. At present such an approximation is all that is possible. On this basis it is now possible to express the climatic humidity well, by the difference of P and E.

CALCULATION OF HUMIDITY VALUES AND DEVELOPMENT OF A POINT MAP OF CLIMATIC HUMIDITY

It has been shown above that E can be figured for any place where T is known, by means of equations 1 and 3. Thus E as presented in the maps was calculated from T by means of equation (1). Then the difference, P - E, was calculated. This is H. Records of air temperature are available for relatively few places (Ångström, 1938), but its average annual value, T, can be calculated for any point from latitude, altitude, and any temperature anomalies that may occur, with functions given by Ångström (1938). Estimation of the annual anomaly is made on the basis of Ångström's map. Such an estimate introduces a new error source, which in individual cases seems to be as much as half a degree centigrade but in general is much less. Many points for determination of E and H are located on annual isotherms, where T can be regarded as known.

Precipitation in Sweden is recorded at about 600 stations, and periodically SMHI publishes maps of the annual isohyets, the latest by Bergsten (1954). In this map the isohyet interval is 50 mm and the period is 1921-1950. It is a serious matter that topography often causes local irregularities in precipitation. Thus values from certain stations are not very representative. This "error" seems less, however, for points selected on the smoothed curves of the map.

All errors in E- as well as in P-values are forwarded to the H-values and added there. This seems to be the primary weakness of the H-values, and is one of the circumstances to be considered in their use. In this connection it must be pointed out that in interior Norrland, Lappland* in particular, there are uncertainties in the meteorological values for the drainages due to the thinness of the station network there. Ångström (1958, page 76), in reference to a discussion of the humidity value and maps based on it, wrote: "These values are the result of some rather rough smoothings and approximations. However, they are of importance in giving a general evaluation..." Thus one must proceed with caution and not attach significance to H-value differences of less than 20 mm when comparing the humidity conditions of different places. Only when the humidity clearly increases or decreases in a certain direction can such small differences be regarded as significant. However, the differences in humidity between different areas in Sweden are often large enough and show such a distinct direction that mapping produces a nuanced picture of the whole that is essentially accurate.

In table 6 are values from some representative stations, with E and H calculated by means of both equation (1) and equation (3). They have been designated E_1 and E_3, and H_1 and H_3. The stations were selected to form several series, each with essentially similar latitudes but with large differences in H-values. One such series is Kalmar-Växjö-Esmared in southern Sweden, and Rönnskär-Malå-Juktfors in northern Sweden.

In plate 1 the 1,172 points used, along with their humidity values, are shown on a map (not reproduced in translation). Because the eastern limit of the mountain region was moved somewhat to the east during the course of the work, this number of points does not agree with the number, 1,263, reported in an earlier publication (Tamm, 1956a). The latter figure also includes some thirty points that happened to be counted twice.

The 1,172 points finally used distribute themselves into the following categories:

1. 177 points that are both temperature and precipitation stations. In plate 1 these are marked by large solid black disks.
2. 417 points that are only precipitation stations. T has been calculated from latitude, altitude and anomaly according to Ångström (1938). They are marked by open black circles.
3. 509 points that are intersects of annual isotherms and annual isohyets on a working map with a scale of 1:1,500,000 worked up by Dr. Magnus Lundqvist. They are marked by small round black dots.
4. 69 points determined in 3 different ways.
    a. Selection on an isotherm with P interpolated between isohyets (more than half the points).
    b. Selection on an isohyet, with T calculated according to Ångström.
    c. Selection on level terrain between two isohyets, with T calculated, and P interpolated between the isohyets.

In the map, plate 1, the points of all three origins of category 4 are marked with blue triangles.

DEVELOPMENT OF A MAP WITH ISOLINES OF CLIMATIC HUMIDITY

Composition of a humidity map with isolines at 50 mm intervals, based on the point map, was taken over by Dr. Lundqvist. He brought to the job the high degree of competence developed in preparing a large number of climatological maps, most recently in "Atlas of Sweden". Dr. Lundqvist has sometimes rejected a point on plate 1 that would not fit harmoniously drawn isolines or would require acceptance of small enclosed areas of a particular humidity around a single precipitation station whose P-value is not permitted by meteorologists to influence the drawing of annual isohyets. These "rejected" points in the beginning amounted to 50-some, a number not considered remarkable by Dr. Lundqvist. Of this more will be said later.

Since the mountain region must be excluded, a suitable eastern boundary for it must be established. Originally the 500 mm isoline was selected. In the final editing of the map, however, the 400 mm isoline proved more suitable. This is the limit between the so-called normal humid region (see below) and the mountain region. Within the latter, precipitation and climatic humidity are extremely variable and also only generally known. Knowledge

of them is based on a thin station network and hydrologic observations. In the region farthest north, from the north shore of Torne Lake* (north of the Gulf of Bothnia*) to the Norwegian and Finnish boundaries, the 300 mm isoline has been used. West of this the terrain is mountainous and has low precipitation, according to meteorologists apparently about 450-500 mm, which corresponds to a humidity of only 300-350 mm. Also, in the vicinity of the mountain region but mainly east of it the humidity value must be regarded as very uncertain. On the map the areas of uncertainty are shown by broken isolines, which begin with the 400 mm line.

On the map, plate 2, the solid isolines of 400 mm humidity value in southern and central Sweden have a different significance than the broken isolines of comparable value in Norrland and in upper Dalarna*. The former are limits between normal-humid areas (see the definitions on page 23) and strongly humid areas within which variations in humidity are marked by isolines of 450, 500, 550, and 600 mm. The broken 400 mm isolines, on the other hand, are the limits between normal-humid areas, and more strongly humid areas within which variations in humidity are very large, from 400 mm to about 1500. Within these strongly humid mountain areas it is at present impossible to construct humidity isolines.

DISCUSSION OF THE POINTS REJECTED IN DRAWING ISOLINES

In shifting the limits of the mountain region on the map, a number of the previously rejected points fell outside the area of humidity differentiation. Only 32 rejected points remained in this area. This decrease, from more than 50 to 32, was undoubtedly related to the fact that in the vicinity of the mountains data are sparse and less representative. Of these 32, 15 deviated insignificantly, less than 20 mm, from the value suggested by the isolines. It is felt that such small errors need no discussion.

Of the remaining 17 points, one belongs in category 1 - the weather station of Kedjeåsen ("Chain Ridge"), northeast of Kristinehamn, elevation 165 meters. It deviates by 56 mm. In this area the precipitation increases rapidly from the shore of Lake Vänern* to the higher more strongly dissected parts of Bergslagen. For reasons of topography a single point here is not very representative.

Of the remaining 16 points, 13 belong to category 2. They are weather stations where only precipitation was recorded. Seven of these lie in strongly dissected Norrland terrain, near the mountains, which is to say their P-values probably are not very representative. One station, Gisselås ("Gissel Ridge") in the province of Jämtland, with an H-value of 259, deviating 41 mm, lies quite near a station whose H-value is 305 mm. This latter

station obviously must be that used to guide the drawing of the nearest isoline. Three stations lie very near the Norwegian border in northwest Värmland*, in strongly dissected terrain where the precipitation is poorly known. (See the reference to the Röjdån drainage, page 7 .) Among other points one deviates rather little (24 mm) but another, Kölaråsen ("Kölar Ridge"), in western Dalarna* near the Värmland* border, elevation 340 meters, deviates more than any other, 126 mm. It seems rather certainly to be in a small isolated area of very high precipitation (856 mm) and humidity (526 mm), represented only by this one station, which is not permitted to influence the precipitation maps of the SMHI. (See Bergsten, 1954.) One station in Bergslagen, Stjärnfors, which deviates by 66 mm, lies in an area where precipitation varies very strongly with topography.

Clearly all the larger "errors" are at points in areas with strongly varying topographically conditioned precipitation.

With category 3 are found only three points that deviate over 20 mm, and those deviate rather little (29, 29, and 38 mm). One of the points lies near the mountain region. The points in question are not strictly fixed in location; a little shifting, decreasing the deviation, can very well be considered justifiable. The small amount by which points in this category deviate from curved values of humidity show the suitability of using intersects of isotherms and isohyets. The values of P read from these intersects are the result of a series of smoothings. Thus, Dr. Lundqvist pointed out, in many cases these P-values are actually more representative than are those of the weather stations. This may also be the case with points in category 4. Here no deviating points were encountered, which, however, may be due to the small number of points.

Detailed scrutiny of the points with relatively large "errors" has led to the conclusion that deviations from values acceptable according to the isolines can easily be explained on the basis of local topography. For this reason one can venture to assert that the network of points with known humidity values, produced here, is relatively sound. At present anything essentially better can hardly be produced on the basis of existing weather recrods. The map of isolines should also be acceptable then.

THE UTILITY OF HUMIDITY VALUES IN AGRICULTURAL AREAS

This investigation is based on data from drainages representing forested Swedish normal terrain formed especially from morain of crystalline rocks. Can the results obtained be applied to agricultural plains? This is a question of interest to Swedish agriculture. It must be pointed out that there are almost no watershed data in Sweden to clarify the humidity conditions of the agricultural plains with any satisfactory degree of certainty.

In preliminary papers (Tamm 1954, 1956a) the author has been cautious in generalizing regarding applicability of E- and H-values to open farm country. Recently, however, Ångström (1958, page 113) has commented on this question. He writes: "From the data available it seems one can say that under conditions prevailing in Sweden evapotranspiration from forested terrain differs insignificantly from that of plains or cultivated ground, if we look at it for the year as a whole." According to Ångström the functions developed above can be used for determination of evaporation from temperature in open farming districts in our country.

Several investigations in Sweden, for example the latest by S. Kihlberg (1958), who also cites considerable earlier literature on the subject, show that E is considerably greater in forest than in nearby non-forested terrain. However, researchers who have compared forest with non-forest from the hydrologic point of view have as a rule compared forest stands with natural vegetation of clearings rather than with cultivated crops. The transpiration of the natural vegetation of clearings is not much known; it increases strongly with time after logging, then decreases after several years. Also, transpiration differs greatly between stands of pine, spruce, and birch. It seems very probable that E is appreciably higher in a fully stocked spruce forest in southern Sweden than in a newly vegetated clearcut within the same forest. In comparisons of such forest stands with field crops, the crop should be specified. There are considerable differences in the transpiration rates of barley, rye, wheat, oats, root crops, oil plants, pasture grasses, and so forth.

The matter of the actual applicability of derived E- and H-values to open agricultural terrain in Sweden seems to be undecided. Probably deviations from the "normal" conditions of this study are not especially large, and under all conditions the H-values can be used as indexes. They are the values that would apply if the terrain had a normal distribution of forest, lakes, bogs, and so forth. As such an index the H-value is better than De Martonne's number, since it is considerably more sensitive to temperature.

Thus, although with some caution, the derived H-values can be used in connection with agricultural problems in which climatic humidity plays a role; they have already been used (Svanberg, Åberg and Steen, 1956). It is worthy of note that our largest and most important agricultural plains for the most part have low humidities. Some, as certain parts of the Östergötland* plain and Visingsö, have very low humidity. Thus less abundant moisture has been no obstacle to very intensive agriculture.

CLASSIFICATION OF SWEDEN INTO HUMIDITY REGIONS

Based on the map of plate 2, a new division of our country into humidity regions can be made (figure 4). Suitable isolines are selected as regional boundaries. The regional boundaries mark gradual transition zones through which the H-values change. In spite of this weakness such a map of regions gives a good geographic review of the humidity conditions in the country. When details are wanted, one can go to the maps of plates 1 and 2; or using equation 3 calculate new values of E and H for a number of points within the area being studied.

Below are listed the regions that, in reference to plate 2, can profitably be distinguished:

1. The subarid region, humidity value $<$100 mm.
2. The weakly humid region, humidity value 100-200 mm.
3. The normal-humid region, humidity value 200-400 mm.
4. The strongly humid region, humidity value 400-600 mm.
5. The superhumid region, humidity value $>$600 mm.
6. The mountain region, humidity value high and very variable.

Some information on the composition of the different regions, their characteristics and relations to agriculture and the forest, follows:

1. THE SUBARID REGION. H $<$100 mm. To this region belongs a very narrow strip of Skåne's south coast*, the southern part of the Lister Peninsula in Blekinge*, a long narrow band along Kalmar Sound*, all the island of Öland*, and most of Gotland's coastal districts*, Visingsö and a not inconsiderable part of the plains of Östergötland* as well as a number of islands in the outer archipelagoes of north Kalmar District, of the provinces of Östergötland, Södermanland, and of the Stockholm District. The region is closely related to Hesselman's subarid region, after whish it is named, but comprises a considerably greater area. On the point map within this region four stations are found with negative H-values (see plate 1). They are:

Stora Karlsö (-62 mm), the southern tip of Öland* (-17 mm), Kappeludden (-20 mm), about half-way down Öland's east coast, and Härad Island (-2 mm), a lighthouse site among the outermost islets outside Valdemars Bay. All these locations are on points into or small islands within the open sea, so are strongly exposed to the wind, which makes exact measurement of their precipitation difficult. Therefore, their negative H-values are not proof of an arid climate. On the other hand the climate in Region 1 does approach aridity rather closely. The natural vegetation and soil profiles of Öland* and Gotland* have many features reminiscent of arid conditions; the generally high lime content of the geologic structure of these two large islands contribute strongly to this appearance. Fresh water supplies on these islands are more critical than elsewhere in Sweden.

2. THE WEAKLY HUMID REGION. H = 100-200 mm. To it belong some of the outer islands and points of land on the west coast, important parts of Malmöhus District* and the Kristianstad plain*, most of Blekinge*, most of interior Gotland* and of Kalmar District* with patches in the districts of Kronoberg* and Jönköping*, a large part of the Västergötland* plain and important parts of Östergötland*, Södermanland* and Uppland* and a narrow coastal strip along the Gulf of Bothnia* nearly to the Finnish border. Other locales of this climatic region are small parts of the Närke* plain and Västmanland*, the country around Lake Runn in Dalarna*, two small areas in the vicinity of the Dellen Lakes in Hälsingland* and in the Ljung Valley in western Medelpad*. The region coincides in part with that which Hesselman designated continental. It is very important, including considerably more than half of our country's most important agricultural plains. Also, the forests of this region often are unusually productive at locales where moisture is not critical, as on sites with relatively high water tables. On the other hand pronounced pine lands are found, for example in eastern Småland*, on which birch and spruce invade with difficulty. These pine lands seem to be related to the weak humidity in combination with rather coarse sandy and sometimes stony till.

3. THE NORMAL-HUMID REGION. H = 200-400 mm. This region includes considerably more than 50 percent of Sweden's surface, and can be said to be normal for our country. Most of Sweden's productive forest occurs in it. The humidity value often lies near 300 mm.

However, there are also important agricultural areas in Region 3. The Göta River region (southwest of Lake Vänern*) and the plains of the west coast, parts of Kristianstad District* and even a small patch of central Gotland* are in Region 3, as are parts of Småland*, Västergötland*, Värmland*, the Lake Vänern area* and most of the farming district in Dalarna* and Norrland. It is noteworthy that the great interior of Norrland outside the mountain region and behind the coastal strip belongs almost entirely to this humidity region. This

is because the air temperature and precipitation decrease together from the coastal zone inward to the limit of the mountain region. In upper Norrland our map differs fundamentally from that of Hesselman.

4. THE STRONGLY HUMID REGION. H = 400-600 mm. This region includes a significant area of interior Bohuslän* and of Dalsland* and Halland*, important parts of Älvsborg District (in Västergötland Province*) and the westernmost parts of Småland*. Large parts of the high sections of Värmland*, Bergslagen and Dalarna* belong to it (but not Dala Mountain and environs, which belong to the mountain region). Interior Norrland aside from the mountain region seems less than strongly humid, except a strip of eastern Härjedalen* toward Orsa Finnmark, another strip in northwestern Hälsingland*, and two insignificant areas in the highland districts of southern Lappland* near the Ångermanland border*. The easternmost of these two extends into Ångermanland.

   Region 4 includes no real agricultural region, although considerable farming occurs locally, especially south of the Norrland terrain. The forest is distinguished by an obvious tendency to form raw humus, often even in deciduous forests (of beech and, in Halland*, also of oak). There are extensive peat formations, difficult to drain and usually unsuited to forest production. Especially in the northern areas, bogs occur abundantly on rather strong slopes. The very high humidity is <u>not generally</u> of advantage to wood production, even if plantations benefit from it. In hill country subirrigation on slopes is favored, and results in local occurrence of highly productive stands.

5. THE SUPERHUMID REGION. H > 600 mm. (All superhumid areas in the mountains are excluded.) The superhumid region, though of rather insignificant area, is very interesting. It combines rather high temperatures with very high precipitation--at least three times as high as in the important Region 2 and up to 10 to 12 times as high in the subarid Region 1. The superhumid region includes level as well as rather strongly dissected areas in interior Halland*, and stretches somewhat across the borders of Västergötland* and Småland*. Tamm (1959) studied it in detail. This study, including discussion of runoff in several rivers in Halland, resulted in a map of the region differing somewhat from the map in plate 2. The reason for the disagreement is the map in plate 2 was made in an early stage of the investigation. The map in figure 4 gives a later, corrected picture of Region 5.

Region 5 corresponds to a degree with Hesselman's superhumid region, for which it is named, but is considerably greater in area. Outside the area shown on the map there are probably a number of high elevation points (outside the mountain region) with superhumid or nearly superhumid climates, in the Borås area, in Värmland*, and in Dalarna*. The Röjdåsen weather station in northwestern Värmland close to the Norwegian border has an average annual precipitation of 998 mm, giving an H-value of 682 mm. The Gråtbäck precipitation station in Dalarna, about 10 km south of Orsa Finnmark at an altitude of 525 m, has a P-value of 839 mm. It is surrounded by hills and plateaus reaching to 700 m. Because of the relatively low average annual temperatures at these elevations, precipitation equal to that at the station should give an H-value of 583 mm. Thus the precipitation must increase only 17 mm with the elevation increase of 175 m to give superhumid conditions. This precipitation increase with height probably exists. The Köleråsen precipitation station in western Dalarna near the Värmland border, at an altitude of 340 m, has a P-value of 856 mm. It lies in a narrow valley surrounded by heights reaching 600 m. If these heights have the same average precipitation as the station their H-values are 576 mm. A precipitation increase of 24 mm with 260 m increase in elevation would put these heights in the superhumid class. Such an increase is probable. These precipitation stations are among those rejected in the drawing of isolines, as their high precipitations represent quite small areas, which can scarcely be delineated on a summary map.

The superhumid region is of little significance agriculturally. It is interesting that very coarse glaciofluvial gravels and sands in this region have been cultivated to a relatively large extent and produce well after fertilization with natural manure; climatic watering here is clearly sufficient even on very permeable soils. From the forestry point of view, what was said of Region 4 applies here; the general tendency toward peat formation is even more pronounced in Region 5.

6. THE MOUNTAIN REGION. From the humidity point of view the mountain region must be considered separately. It deviates from the other regions by, above all, its great variations. In general its humidity is more than 400 mm, farthest to the north over 300 mm. It rises quickly with increased elevation, on the highest mountains reaching a maximum of 1400-1500 mm and perhaps more. Considerable areas seem to have H-values of 800-1000 mm. These assumptions are based on calculations by meteorologists of average annual precipitation, these calculations resting on a rather thin network of meteorological stations and runoff measurement in a number of streams. (See C. C. Wallen, 1951, pages 5-11, and Bergsten, 1954, page 4.) The average annual evapotranspiration in the mountains is

lower than in the rest of Scandinavia, due to low temperatures. Melin (1942) estimated it at 150 mm per year in the Malmagen mountain region; this has since been generalized as approximately true for the mountain region as a whole (Wallen, 1951, page 7, and Bergsten, 1954, pages 4 and 7). On the precipitation maps prepared by these researchers the isohyets have been related for the most part to topography and altitude. The basis for humidity estimates has been these SMHI precipitation values diminished by 150 mm. Here and there are weather stations from whose precipitation measurements local humidity values can be derived. Their applicability, however, is restricted pretty much to the location where obtained.

THE HUMIDITY VALUE AND THE CONTINENTALITY AND MARITIMITY OF THE CLIMATE

One rather generally encounters the idea that a highly continental climate means low precipitation and therefore low climatic humidity. In many cases this is not so. Continentality is a matter of temperature, usually measured as the difference in the average temperatures of the warmest and coldest months. Ångström (1938) has distinguished a number of local continental and maritime areas in Sweden. The local continental areas have somewhat warmer summers and colder winters than is normal for their latitudes in Sweden. The converse is true for the local maritime areas. Comparison of the local continental and local maritime areas with humidity regions is of interest. The most pronounced local continental area includes almost all of Värmland*, and of Dalarna* west of a line from Leksand to Rättvik, as well as almost all of Härjedalen* and small parts of southern Jämtland* and western Medelpad*. Even ignoring the mountains in northwestern Dalarna and in Härjedalen, this area has generally <u>high</u> humidity except in the valley of Österdalälven where the humidity is quite low. Large parts of the area belong to the strongly humid region, small areas of heights and plateaus even seeming to have superhumid climates. Here is no correlation between high continentality and <u>low</u> humidity, but rather the opposite. The poor heather-rich ground vegetation so important in the poor pine forests of northwestern Dalarna and in Härjedalen has sometimes been referred to as the result of the dry continental climate. The climate is not dry. The reason for this area of pine dominance, its ground vegetation type and low productivity, is the mineralogically poor land composed mainly of quartzites, quartz sandstones, and porphyries. Where the parent rock is more favorable (diabases), the forests are richer in spruce and more productive.

Ångström's local continental area in southern Sweden belongs in part to the weakly humid region, and thus could be said to suggest a relationship between continentality and low humidity. Both the continentality and the humidity decrease eastward toward the coast, however. In the coastal zone of northern Kalmar District the climate is local-maritime and at the same time very dry--in the outermost coastal strip even subarid. In all this area increasing continentality coincides with increasing humidity, rather than the opposite. The same is true of the west coast, where Ångström distinguishes a rather pronounced local maritime region. Here maritimity drops quickly inland, while the humidity increases considerably.

According to Ångström the Scandinavian mountain chain has a local maritime climate for the most part, while a broad strip inland between the mountains and the east coast has a local continental climate. Here correspondence does prevail between high humidity and maritimity and between rather low humidity and greater continentality. The high humidity and also the maritimity in the mountains is due to the proximity of the Atlantic. The local continental inland strip has both low precipitation and a low average temperature, which combined result in a uniformly moderate humidity.

It is obvious that in Sweden there is no general relation between high continentality and low humidity or between high maritimity and high humidity.

CLIMATIC HUMIDITY AND THE FOREST

The particular purpose of this investigation was to provide a tool for Swedish forest science. This branch of applied science has long needed a good quantitative expression of humidity to characterize the conditions under which the forest is growing and producing, as on many test plots. In the absence of anything better De Martonne's number has been used, or simply average annual precipitation. Now in any discussion of the influence of average precipitation and humidity on the forest one should also give the H-value.

The climatic aspect of water supply, of which the H-value is a measure, is only one side of the moisture problem for the forest and the natural vegetation. This problem also involves to a high degree the permeability and retentiveness of the ground, and the level and perhaps the mobility of the ground water. The climatic humidity exercises considerable influence on the ground

water level, since in our country practically all ground water originates from precipitation. On the other hand, atmospheric humidity, which is also important to plants, is not related to climatic humidity, being especially high in the subarid coastal strip, for example.

For many purposes it would be very worthwhile to get monthly and seasonal values for the humidity of our climate. The complex of problems associated with this must be solved in some other way, however. Ångström (1936) has been interested in this. Turc's (1954-1955) lysimeter studies aimed at clarification of, among other things, the soil moisture balance of the different months. Many other researchers in different parts of the world are presently working with problems of that sort, mainly in agronomy.

The moisture condition of forest land is determined by a whole complex of factors, among which the H-value, though important, is only one. Therefore without knowing more than we do, it is usually hard to evaluate its role. In some cases, however, it seems possible to do so. Some examples are given:

Lichen-rich pine forests are generally not common in regions with high humidity, and when they do occur there (as in northwestern Dalarna) they are virtually always caused by nutrient poverty of the soil. In weakly humid regions, thick gravel and sand deposits where tree roots do not reach ground water have low productivity and contain insignificant elements of birch and spruce, even where the mineralogical character of the soil is relatively good.

If the topographic-geologic conditions permit lateral movement of ground water that is reached by tree roots, high climatic humidity often leads to very productive slope stands. An example is the Hamra Forest District in Orsa Finnmark (Tamm and Wadman, 1945). Here the average site quality and the occurrence of spruce increase with altitude due to abundant lateral filtration of ground water in the rather strongly humid and dissected highlands. However, a highly humid climate is not always beneficial. In the Kristinehamn Forest District (north of Lake Vänern*), in a region where precipitation and humidity value increase strongly northeastward, Gabrielsson (1948) stated silviculture in the areas of high humidity must be based in part on different methods of regeneration and thinning than in the less humid areas, due to a tendency toward the development of microbiologically inactive raw humus where humidity is high.

The extent, composition and drainability of peat bogs depends on two chief factors: humidity and topography. The enormous extent of peats on the rather flat Esmared Plateau

of Halland's* superhumid region has been discussed by Tamm (1959). Comparison with the similarly level landscape of southern Småland* to the east, where the H-value is much lower, points out the importance of the humidity.

SUMMARY

The results of these investigations may be summarized as follows:

1. Equations (1), (2), and (3) have been derived for calculation of average annual evapotranspiration, E, from average annual temperature, all for Swedish normal terrain. Equation (3) is considered best. The E-values gotten are approximate expressions of the total water vapor loss from normal Swedish forest terrain.

2. A map (figure 3) has been developed for Sweden with isolines of evapotranspiration.

3. The humidity values in mm, that is, the difference between average annual precipitation and average annual evapotranspiration for the same series of years, have been calculated for a large number of points outside the mountain region, and were marked on a map of Sweden (plate 1). The humidity value represents that fraction of the average annual precipitation which escapes evapotranspiration. In other words it is a measure of the climatic aspect of water supply.

4. On the basis of the point map, a map of Sweden (plate 2) outside the mountain region was prepared with humidity value isolines at 50 mm intervals.

5. On the basis of the map of plate 2, Sweden has been divided into six humidity regions: subarid, weakly humid, normal-humid, strongly humid, and superhumid outside the mountain region. (See figure 4.)

6. It has been shown that in Sweden there is no general relation between continentality of climate and low humidity or between maritimity and high humidity.

7. Some general relations have been touched upon between humidity of climate on one hand and certain forest conditions on the other. The H-value is an important component in the complex of natural factors that condition growth and production of the forest.

8. The most important result of the investigation seems to be the establishment of simple equations for calculating evapotranspiration from average annual temperature, which then permits calculation of the humidity value, H, from average annual precipitation. In many cases, at places where temperature and precipitation values are available, it is better to figure E

and H directly than to take them from the map. Later, of course, new means will be developed from data for later periods to be published by SMHI; the maps presented here will become obsolete to a degree. Equation (3), $E = 221.5 + 29.0\ T$, is the best for calculating E. The chief purpose of the maps is to give a geographic review.

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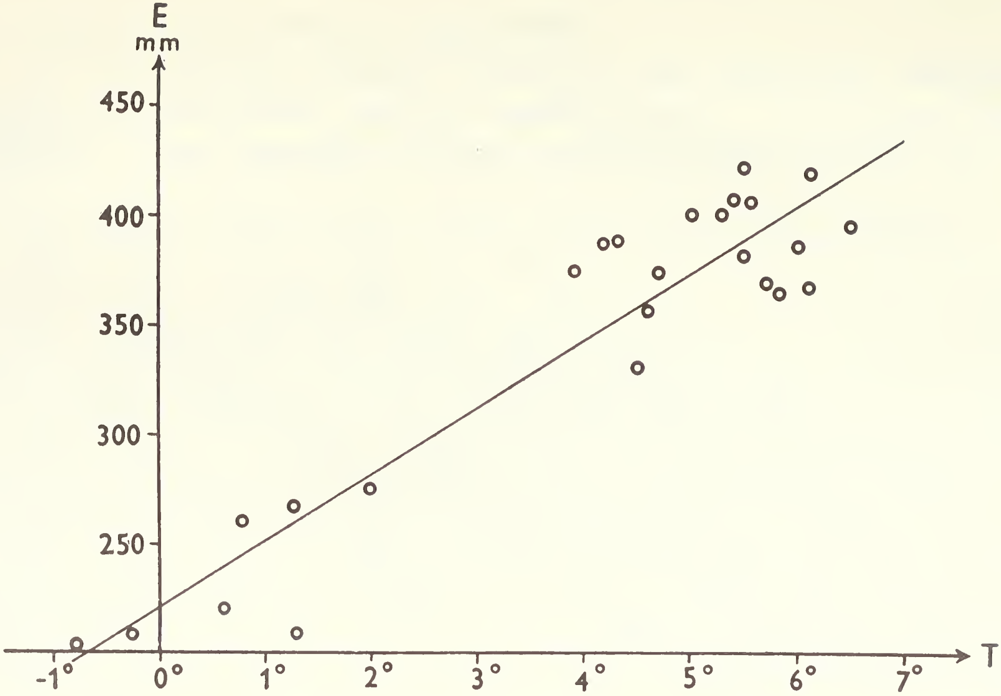

Figure 1. The average annual evapotranspiration, E, as a function of average annual temperature, T, in the drainages of 25 Swedish rivers outside the mountain region. Each point represents a drainage.

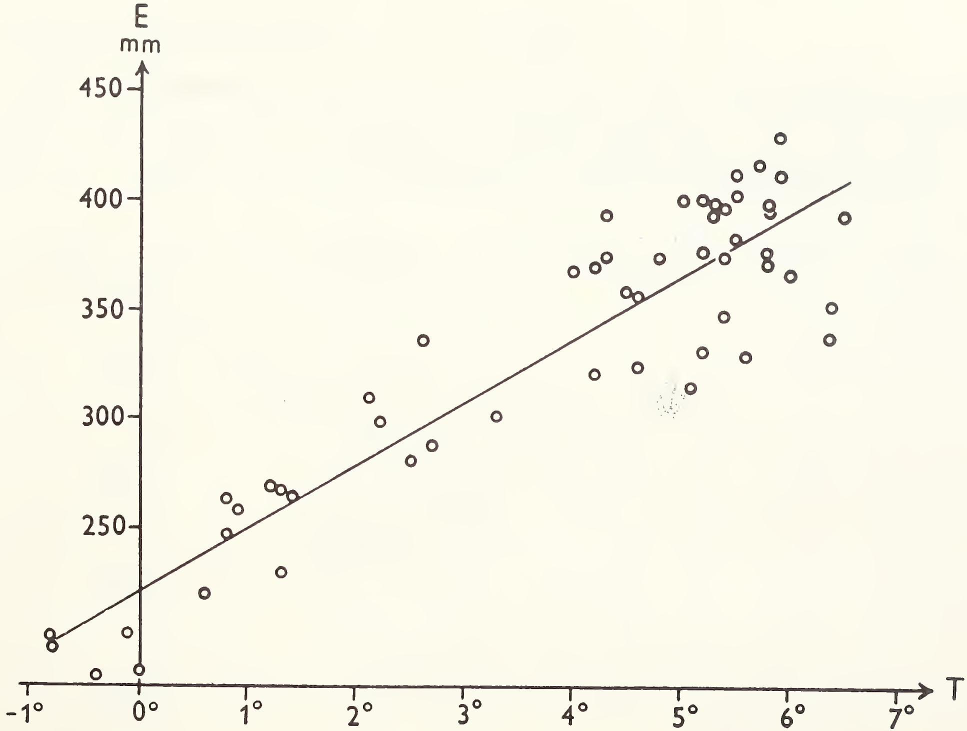

Figure 2. The average annual evapotranspiration, E, as a function of average annual temperature, T, in the drainages of 53 Swedish rivers outside the mountain region. Each point represents a drainage.

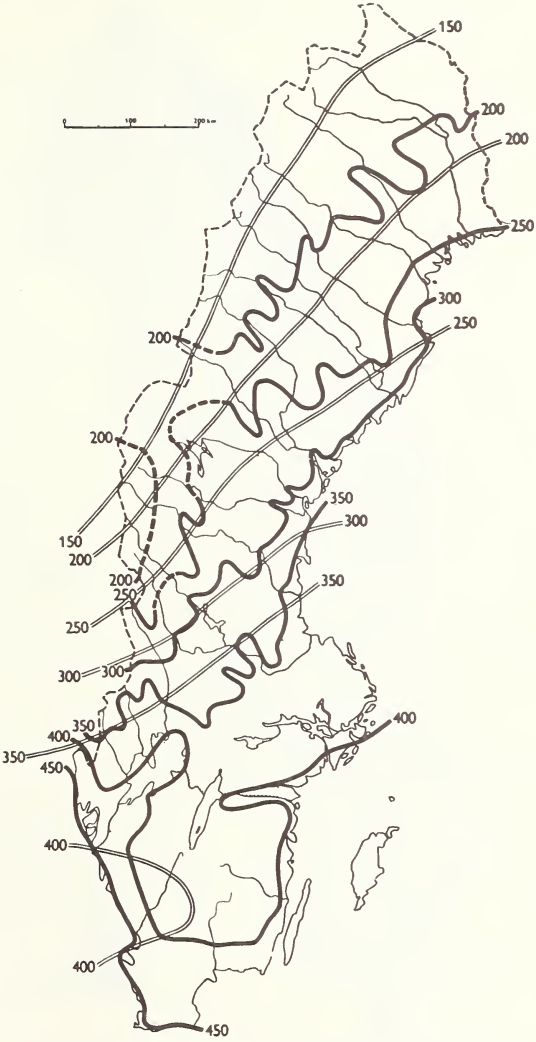

Figure 3. Map of the average evapotranspiration in Sweden, in mm. The black isolines are based on Tamm's equation (1). Essentially they are isotherms with intervals corresponding to 50 mm of evapotranspiration (see table 5, page 15). The light double lines are evapotranspirations (according to Bergsten) arrived at with the help of watershed investigations.

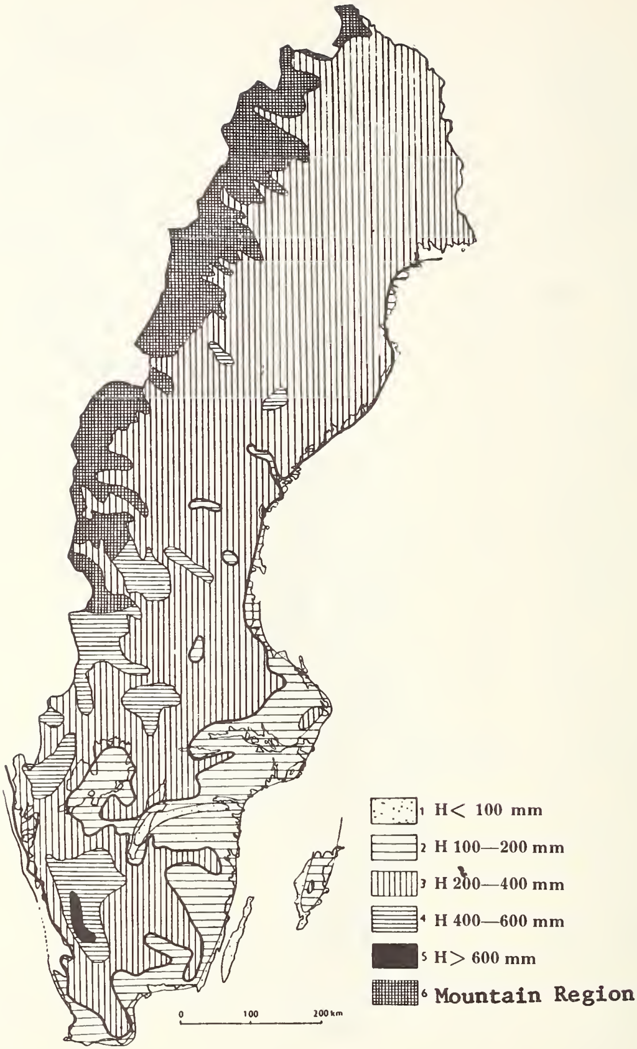

Figure 4. Sweden's humidity regions according to Tamm: (1) The subarid region, (2) The weakly humid region, (3) The normal-humid region, (4) The strongly humid region, (5) the superhumid region, (6) The mountain region, where the humidity varies strongly from 400 mm (in the far north 300 mm) to about 1500 mm.

Table 1. Drainages used, and data from them.

Streams and Gaging Stations	Area	S	T	Alt.	B	P	A	E
	km²	%	°C	m	m	mm	mm	mm
1. Lappträskån, Ytterholmen ...	1040	2,3	— 0,8	250	223	544	347	197
2. Råneälv, Niemisel	3770	3,3	— 0,8	285	294	534	342	202
3. Sangisån, Kukkasjärvi	502	8,7	— 0,4	130	126	530	347	183
4. Byske älv, Myrheden	2430	6,7	— 0,1	430	360	585	382	203
5. Åby älv, Björkliden	616	10,2	± 0,0	405	235	564	379	185
6. Öre älv, Nyåker	2760	2,5	+ 0,6	370	323	586	366	220
7. Sävarån, Stenfors	661	10,0	+ 0,8	270	216	588	325	263
8. Lögde älv, Häggnäs	1360	4,4	+ 0,8	375	323	610	364	246
9. Gide älv, Björnafallet	3020	5,0	+ 0,9	355	259	597	338	259
10. Moälven, Mellansel	1450	4,0	+ 1,2	285	308	609	341	268
11. Kåge älv, Kåge	897	2,5	+ 1,3	240	276	559	329	230
12. Gimån, Gimdalsby	2180	12,8	+ 1,3	365	190	544	278	266
13. Bure älv, Bodbyn	520	5,2	+ 1,4	190	182	586	322	264
14. Vanån, Vanåbodarna	2280	5,7	+ 2,1	405	288	692	382	310
15. Norsälven, Önnerud	836	2,9	+ 2,2	335	248	760	461	299
16. Delångersån, Rolfsta	1830	11,3	+ 2,5	245	314	575	294	281
17. Voxna älv, Stagården	3700	6,1	+ 2,6	335	373	647	310	337
18. Harmångerån, Franshammar	660	3,6	+ 2,7	315	240	622	334	288
19. Lillälven, Borgärdet	1850	9,2	+ 3,3	290	221	614	313	301
20. Gavleån, Övre Gävle	2460	9,2	+ 4,0	160	346	635	266	369
21. Sverkestaån, Kärsbohammar	417	6,2	+ 4,2	180	158	719	348	371
22. Gullspångsälven, Åtorp	4420	10,8	+ 4,2	230	323	731	410	321
23. Kolbäcksån, Hallstahammar	2970	9,0	+ 4,3	210	274	671	276	395
24. Tämnarån, Odensfors	772	6,3	+ 4,3	52	48	585	209	376
25. Dyltaån, Hammarby	890	9,5	+ 4,5	185	238	741	382	359
26. Hedströmmen, Ekeby	1020	8,5	+ 4,6	155	217	664	307	357
27. Fyrisån, Uvlunge	263	2,6	+ 4,6	35	51	565	240	325
28. Huskvarnaån, Tokarp	603	8,2	+ 4,8	265	93	647	272	375
29. Östergötl. Svartå, Rövartorp	1920	12,8	+ 5,0	205	122	565	164	401
30. Vattholma å, Vattholma ...	284	4,8	+ 5,1	35	30	560	244	316
31. Olandsån, Fors	576	3,2	+ 5,2	27	20	550	218	332
32. Emån, Järnforsen	1900	8,3	+ 5,2	230	100	606	228	378
33. Tofstaån, Sölaryd	1210	9,6	+ 5,2	225	152	714	313	401
34. Nerikes Svartå, Hasselfors .	688	10,7	+ 5,3	ca 100	179	697	298	399
35. Ätran, Kila	2520	6,6	+ 5,3	190	171	872	474	398
36. Nissan, Johansfors	2440	5,3	+ 5,4	190	148	830	481	349
37. Velenån, Velen	47	9,0	+ 5,4	130	20	625	227	398
38. Stångån, Sätra	2230	11,2	+ 5,4	150	142	577	202	375
39. Nyköpingsån, Täckhammar .	3580	14,0	+ 5,5	50	151	571	187	384
40. Sörån, Rörvik	162	17,6	+ 5,5	220	90	667	253	414
41. Lagan, Århult	5480	10,2	+ 5,5	195	182	758	354	404
42. Alsterån, Getebro	1340	6,5	+ 5,6	185	96	573	243	330

Table 2. Regression equations.

	Equation Number 3	4	5	6
Constant term	221.5±7.7	227.4±14.7	222.3±6.9	164.1±30.2
Coeff. for T	29.0±1.7	21.8± 3.4	22.7±2.4	21.5± 4.2
S		-0.869± 2.184		-0.488± 2.105
ST		0.900± 0.459	0.737±0.207	0.851± 0.446
P				0.087± 0.052
B				0.039± 0.053

Table 3. Sums of squares of deviations, degrees of freedom, and mean squares for the regressions. Calculation of variance quotients.

	Sum of Squares	Degrees of Freedom	Mean Squares
Variation around:			
The average	251,827	52	4,842.8
function 3 (T)	39,346	51	771.5
4 (T, S, ST)	31,306	49	638.9
5 (T, ST)	31,408	50	628.2
6 (T, S, ST, P, B)	27.737	47	590.1
7 (T, P, B)	35,595	49	726.4
Differences:			
(7)-(6)	7,858	2	3,929
(4)-(6)	3,569	2	1,785

Variance ratios:

Test of the influence of S: 3929/590.1 = 6.66

Test of the influence of P and B: 1785/590.1 = 3.02

Table 4. E calculated for different temperatures by means of equations (3) and (1).

T C^o	$E_{(3)}$ mm	$E_{(1)}$ mm	$E_{(3)}-E_{(1)}$ mm	$\frac{2(E_{(3)}-E_{(1)})100}{E_{(3)}+E_{(1)}}$ %
-1	192.5	190.6	+1.9	1.0
0	221.5	220.9	+0.6	0.2
+1	250.5	251.4	-0.9	0.4
+2	279.5	281.8	-2.3	0.8
+3	308.5	312.2	-3.7	1.1
+4	337.5	342.6	-5.1	1.5
+5	366.5	373.0	-6.5	1.8
+6	395.5	403.4	-7.9	2.0
+7	424.5	433.8	-9.3	2.2

Table 6. E- and H-values for some Swedish localities.

	Lat.	Alt.	T	P	$E_{(1)}$	$E_{(3)}$	$H_{(1)}$	$H_{(3)}$
		m	C°	mm	mm	mm	mm	mm
Gällivare	67°50′	358	— 0,6	545	203	204	342	341
Pajala*	67°10′	176	— 0,4	477	209	210	268	267
Haparanda	65°50′	7	+ 1,0	572	251	251	321	321
Juktfors*	65°17′	430	— 0,3	707	213	212	494	495
Malå	65°11′	320	— 0,2	502	215	216	287	286
Rönnskär*	65°03′	5	+ 2,3	418	291	288	127	130
Kulbäcksliden*	64°15′	200	1,9	523	279	277	244	246
Umeå	63°47′	11	2,6	603	300	297	303	306
Östersund	63°10′	333	2,4	531	294	291	237	240
Sveg	62°05′	356	1,7	562	273	271	289	291
Bjuråker	61°50′	66	3,7	524	334	329	190	195
Lillhamra*	61°40′	425	1,8	745	276	274	469	471
Transtrand*	61°05′	355	2,3	769	291	288	478	481
Norrsundet*	60°55′	5	5,0	465	373	367	92	98
Siljansfors	60°50′	260	3,2	705	318	314	387	391
Rankhyttan*	60°30′	130	4,5	500	358	352	142	148
Bjurfors*	60°10′	125	4,6	661	361	355	300	306
Uppsala	59°50′	24	5,2	562	379	373	183	189
Filipstad	59°40′	141	4,7	769	364	358	405	411
Karlstad	59°20′	47	5,9	639	400	393	239	246
Stockholm	59°20′	44	5,9	579	400	393	179	186
Örebro	59°15′	51	6,1	622	407	398	215	224
Linköping	58°30′	96	6,3	528	413	404	115	124
Skara	58°25′	117	5,5	609	388	381	221	228
Visingsö*	58°10′	110	6,2	431	409	401	22	30
Jönköping	57°50′	97	6,8	556	413	404	143	152
Flahult	57°40′	224	4,8	711	367	361	344	350
Göteborg	57°40′	16	7,7	669	455	445	214	224
Visby	57°40′	28	6,9	510	431	422	79	88
Buttle, Gtl.	57°25′	48	6,1	620	406	398	214	222
Esmared, Hall.*	56°43′	170	6,0	1120	403	396	717	724
Växjö	56°50′	183	6,3	670	413	404	257	266
Kalmar	56°40′	7	6,8	475	428	419	47	56
Mörbylånga	56°30′	5	6,6	521	422	413	99	108
Karlshamn	56°10′	7	7,2	570	440	430	130	140
Kristianstad	56°05′	6	7,5	593	449	439	144	154
Lund	55°40′	38	7,2	603	440	430	163	173
S:t Olof*	55°40′	110	6,6	793	422	413	371	380
Malmö	55°40′	3	7,7	555	455	445	100	110

(1) and (3) refer to the equation used.

* Values for these places were calculated. Regarding precipitation at Esmared, see Tamm (1959). Values for localities not so marked are from SMHI observations.

PLATE 2

THE HUMIDITY OF SWEDEN'S CLIMATE

OUTSIDE THE MOUNTAIN REGION

by

OLOF TAMM

Cartography by Magnus Lundqvist

(adapted)